PERFORMANCE AND IMPACT OF CRYOGENIC PULSATING HEAT PIPE USING A DIFFERENT NUMBER OF TURNS AND HELIUM GAS

by

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The present work involves the development of helium based pulsating heat pipe (PHP), which containing 48 parallel tubing parts. The PHP is considered as one of the best alternatives for conducting metals and it is used for long distance heat transfer process. Their heat transfer capability and efficient thermal conductivity are the prominent properties which considered for applications. The region of the condenser was thermally sealed to the giffored mcmohanon cryo-cooler using a cooling cap of 1.49 W at 4.2 K while 1.1 W of heat are allowed to the evaporator section at a filling rate of 70%, through comparing the 48-turn PHP and 8-turn PHP, a most intense efficient thermal conductivity of 12329 W/ mK was achieved in the 48 turn PHP. The influence of no turns of warm movement execution was observed with the same operating parameters and topographical parameters. Observations revealed that the temperature variations of PHP 48-turn was significantly less than that of PHP 8-turn. It exhibited efficient thermal conductivity, high capacity heat transfer and a good dry-out temperature response. Thus PHP 48-turn of series and parallel configurations are defined as excellent system designs and are accessible to the PHP cryogenics framework architecture.

Keywords**:** *cryogenics, pulsating heat pipe, heat transfer, helium, evaporator*

Introduction

Condition-cooled systems are significant for their performance, safe handling, low operating costs and fast handling using a light mass cryo-cooler for superconductor magnet applications. In case of heat transfer between superconductivity magnet and cryogeniser, high

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conductivity copper with a thermal conductivity at 4.2 K is around 660 W/mK is used. A 44 mm copper rod is necessary to transmit 1 W power for cooling from the cold head to the super conductivity magnet with a difference in temperature of 1 K and 1 m apart. When the distance is increased to 10 m, the diameter of the copper rod will be increased to 139 mm which is unfeasible as there is a huge loss of volume/mass. Figure 1 displays a schematic diagram of a PHP closed loop, a device with two phase capable of heat transfer. The small capillary channel flows in a circuitous way and reaches the inlet end. The tube diameter must be in such a way that it is enough for the working fluid for alternative vapour bubble and liquid sludge distribution. The adiabatic, condenser and evaporator sections contain PHP that is similar to the typical heat pipe.

Performance of PHP heat transfer is affected by various parameters like cross-section shape, inner diameters, length of the evaporation section, channel configuration, liquid fill ratio (LFR), number of turns, heat flux, inclination angle, non-condensable gases, the tube internal surface features, *etc*. [1, 2]. Summary of previous helium PHP experiments is given in tab. 1. Many experiments have been conducted at room temperature for understanding the working mechanism of PHP using working fluids such as water, R123, ethanol, nanofluids, acetone, methanol, R134a, *etc*. and visualization of experiments are recorded with the help of good quality high speed cameras [3]. It is noted that there are two states of power in PHP, such as slug and annular flows [4]. The oscillation of continuous motion and the circulation of single direction were the classification of working fluids to modes of motion [5]. Aimed at studies in cryogenic systems, oxygen, helium, hydrogen, and neon based PHP are widely found in working fluids. The thermal conductivity fill ratio was measured in 2014 using a horizontal 60 PHP through 990 mm of adiabatic area length. Prior experiment we used 8-turn PHP, the length of which were 50, 50, and 100 mm, respectively, for evaporator, condenser, and adiabatic sections [6]. The test report shows the most efficient that thermal conductivity was obtained at a helium fill ratio of 70.8% at 15625 W/mK and was vertically focused [7]. In addition, the angle of inclination, heat load and fill ratio depend on these experiments and other PHP cryogenic fluid-based experiments. One of the important factors the designing of PHP is the number of turns and it has been investigated in our experiment. Through this experiment, the 8-turn and 48-turn heat transfer performance of helium PHP is examined and almost combined through its operating mechanism [8, 9].

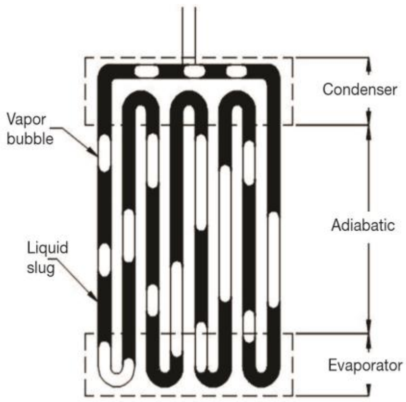

Figure 1. Schematic diagram of a closed loop PHP

Table 1. Summary of previous helium PHP experiments

Previous helium PHP experiments: summery					
Number of turns	Angle inclination	Fil ratio	Diameter (inner) [mm]	Power transfer (maximum) [W]	Section length [mm]
5	0-40	–	0.5	0.273	92
60	0	50	0.5	0.612	90
42	90	20-90	0.5	1.185	3--
8	15-90	24.6-70.8	0.5	1.29	100

Experimentation

Proto types of PHP-helium

In order to shape thermo hydrodynamic oscillations, the working fluid will create alternative distribution plugs such as vapour and air. According to the output obtained, the critical diameter can be formulated:

$$D_{\text{crit}} \leq 2\sqrt{\frac{\sigma}{g\left(\rho_1 - \rho_V\right)}} \tag{1}$$

The 0.5 mm and 0.8 mm inner and outer diameter stainless steel capillary tubes were selected and the unit satisfied the equation. When helium was the working fluid, the measurements of the stainless steel capillary tubes in this experiment have also the same dimensions. The total capillary tube length is measured as 12 m. Sections of evaporator and condenser are 24 used with 48 channels in closed loop PHP. The ends of the loop were attached with the help of a custody tube by a 340 stainless steel *T*-shape joint to provide a comfortable structure by the four layers of the bent on the tube with a space of about 4 mm each. The lengths of which are 50, 50, and 100 mm, respectively, for evaporator, condenser, and adiabatic sections. The length of the three sections and size of the capillary tube is similar in dimension as per previous PHP helium with 8-turn. To avoid the heat loss effect since inlet gas through an extent, copper block nearby the tube charge is linked to the giffored mcmohanon cry-cooler [10-13]. For monitoring the temperature, thermometers were used with the type of rhodium-iron resistance is connected to copper blocks of condenser and evaporators.

System of heating and cooling

For cooling the experimental apparatus, power of 1.5 W at 4.2 K capacity of two stage giffored mcmohanon cry cooler was used. For improving thermal contact of condenser sections of second stage cold flanges of copper block and cry cooler by applying the contact grease and an indium foil. Heating wire is a manganese piece and it is joined to the copper blocks of evaporator area. The PHP helium apparatus be located safely reserved privileged the vacuum chamber and it is propelled vacuum high for to avoid the conduction and convection. For the second stage, a thermal jacket is used at 30 K and 4 K thermal jacket was paired with the cryo cooler's 1$^{\text{st}}$ and 2$^{\text{nd}}$ stage cold flanges both for order to decrease the heat radiation. The thermal jackets are lined through the 30-layer MLI blanket, and the copper blocks in the condenser and evaporator portion are fitted with 15-layer MLI blankets to reduce the load of heat radiation. Consequently, the loss of heat of helium PHP would be quite small, and the power of heating is given by the heater close to the areas of the evaporator may be considered as the entire heat emitted through the helium PHP.

System of controlling

Measuring devices and system data acquiring are the experimental set-up in this process. A data collection device was compelled to test the control electronics using general purpose interface bus for an IEEE-488. The data acquiring process were to automate by a custom designed of data obtaining program in a custom designed manner which is based under the lab view software. By a temperature controller of Lakeshore 332S the condenser temperature were controlled. Through the combination of current and voltage we can determine the strength of heating, the heating wire is driven via keithley 2425 source meter at a evaporator. In keithley 3706, the millimeter attached to the device measured the heating energy, pressure and temperature.

Charging system of helium

In condenser, the gas is applied near the PHP both dissolves at a condense temperature through theentire volume of LFR for PHP were like a coefficient in-between the sum of helium liquid. Pressure in a load tube may be small since the charge tube's inner diameter is 0.3 mm. The LFR can then be determined from:

$$LFR\% = \frac{(P_1 - P_{1*})V_1}{RT_1 \rho_l V_{\text{PHP}}} 100 \tag{2}$$

The present work, aimed at 8-turn PHP is 70.8% and for 48-turn PHP is 70.5% in LFR. The LFR was known thru liquid actual volume divided by the PHP entirevolume. If an 8-turn PHP is 66.4% and for 48-turn PHP is 66.1% in LFR. Approximately 6% PHP error compares experimental results with former cryogenics. Figure 1 displays the schematic diagram of charging of system and fig. 2 shows the experimental set-up. The V1 valve is used to separate from PHP Core to the buffer tank, the V2 valve is located between the vacuum pump and the gas line, the V3 valve in the control system to maintain the total mass-flow rate. Before charging, V1, V2, and V3 valves are locked. Residual gases in the PHP of buffer tank and the charge tube were cleaned by using the vacuum pump. Formerly, V3 valve is closed and valves V1 and V2 are in open. 99.99% of helium gas is converted into helium PHP, and the buffer tank. To ensure purity repeat the process for five times, gas of helium are charge addicted to PHP when purification process exceeds then the buffer tank. Initial pressure of helium is denoted by the P1 which is measured by pressure transducer in the buffer tank, and V1, V2, and V3 valves are locked as illustrated in the fig. 3. To cool the PHP core the giffored mcmohanon cryo cooler was switched on in constant operating temperature. The PHP pressure in the buffer tank

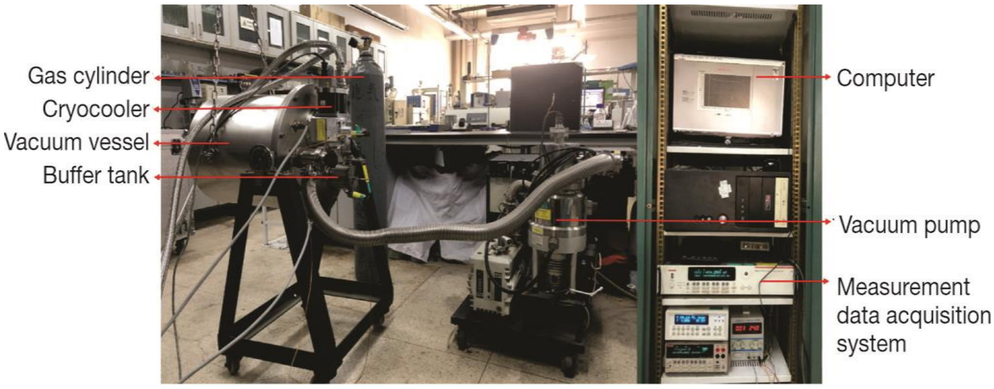

Figure 2. Experimental set-up

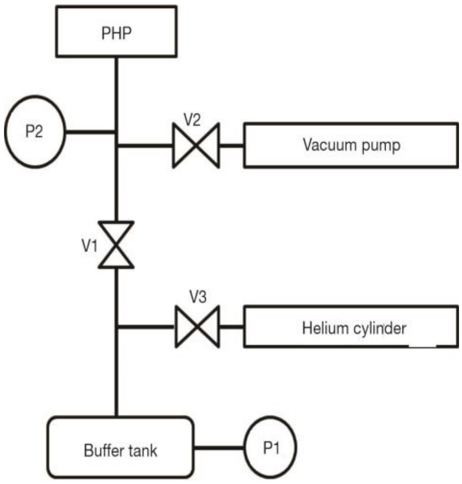

Figure 3. Charging system block diagram

and charge tubeare due to condensation in the PHP. Avoid any mass or thermal exchange between tank and the PHP core by reducing the buffer tank pressure P1, the valve between both the charge and the tank, V1, is eventually lowered. Therefore, P2 is the pressure transducer which will imitate the PHP condenser portion pressure in the room temperature of charging tube.

Procedures for experimentation and analysis of uncertainty

After PHP helium has decreased the working temperature, the control of heating is turned on. When reaching pseudo state the temperature signals by varying the mean value and the helium PHP pressure and evaporator temperature is increased. Sections of evaporator and condenser temperatures are measured and observed.

Through the method which proposed by the Moffatt [14] were calculated the uncertainties in experimental results. The accuracies of resistance thermometer in rhodium-iron were arranged to be ±0.1 K. From the range of pressure between 0 MPa to 1.5 MPa the pressure sensor was arranged through an accuracy of 0.5%. Due to an instability of investigational thermal conductivity with temperature and pressure calculation deviations, the capacity of heating is below 5%.

Result and discussions

Impact on the number of turns

Sections of evaporator and condenser temperature are often in steady state from 0 W to 1.29 W in a short response period, as shown in fig. 4(a). Temperature characteristics by increasing 8-turn helium PHP power supply in a vertical orientation with a fill ratio of 70.8%. Furthermore, whenever the heat charge rises near 1.4 W, the average temperature of the cold head of the second phase is 4.8 K, the cryo cooler's cooling power at this stage is sufficient to keep the PHP device balanced. In the section of the evaporator the liquid quantity is not adequate to transfer the heat because the evaporator temperature constantly rises. In addition, PHP is autonomous, and can no longer function as a heat transfer system based on it. Normally, PHP could not function in the extreme heat transfer, which transfers the heat capacity of the PHP which provides the power of the input.

In fig. 4(b) shows the vertical orientation with a same fill ratio of the 48-turn in temperature behaviour. At first, the temperature stays at 6 K as the power of heat raised nearby 1.2 W, but quickly increases to 7 K and then decreases to 6.3 K. Throughout a broad temperature range, the evaporator goes up and down by quickly raising the heating power above the

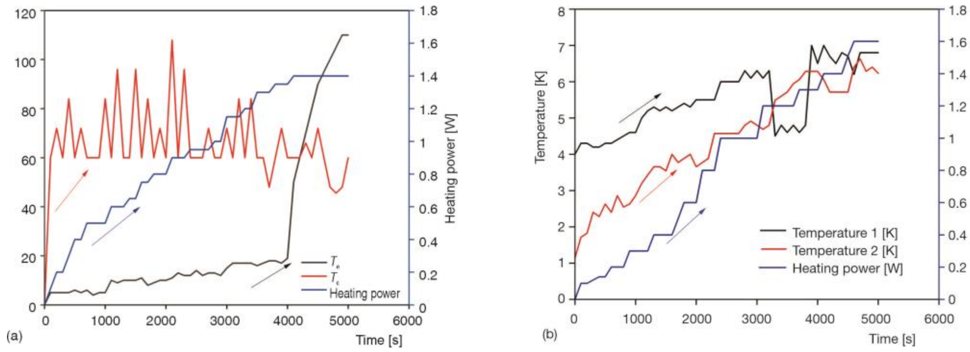

Figure 4. Temperature activity with power up from heating; (a) PHP 8-turn and (b) PHP 48-turn

stage, and in some section in the evaporator, dry out may be formed. In heat transfer system, PHP is ineffective for heat loads greater than 1.1 W, if full dry out phenomena is not being identified. Ineffective is compared to the temperature response of 48-turn PHP process is called *semi dry out* state. In PHP 8-turn the temperature variation between the condenser and evaporator which was shown in the fig. 5(a). With this heating power PHP can work effectively as high as 1.29 W, the temperature is maximum for implementations due to a little quantity of fluid working. By rapidly decrease the heating power there is a temperature variation to the condenser and evaporator for the PHP 48-turn revealed in the fig. 5(b).

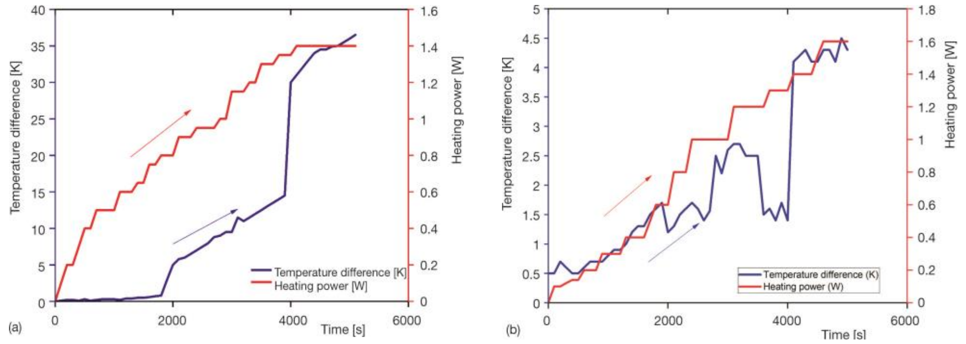

Figure 5. Temperature variation between evaporator and condenser; (a) PHP 8-turn and (b) PHP 48-turn

Figure 6 shows that the comparison of effective thermal conductivity and heating power. In cryo cooler to conduction cooled cryogenics system decreasing the temperature difference of the subjects due to the bounds of cooling power and consistent to the temperature of cold head enrich for efficient to utilization of cooling power. The evaporator temperature is fine overhead the critical temperature of helium which is observed from the PHP of 8-turn and 48-turn. When operating in these conditions the phase flow does not exists in the evaporator. The temperature difference is quite larger between the evaporator and condenser but PHP is still operating in these conditions. Once it hits the supercritical service, the evaporator is totally in the single step, helium is behaving as a working fluid in the operating system of PHP but displaying characteristics is quite distinct to the other working fluids.

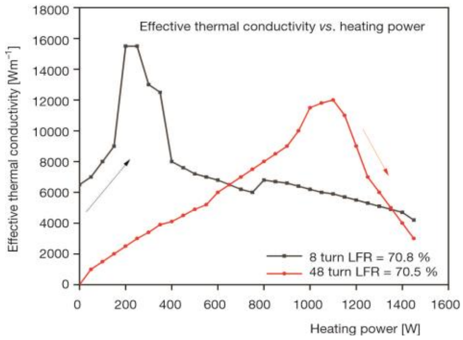

Figure 6. Comparison of effective thermal conductivity and heating power

From the evaporator and condenser temperature at all heat power, the thermal conductivity, λ, and the heat flux, $\dot{q}$, were obtained by:

$$\lambda = \frac{4LQ}{n\pi d^2 \left(\overline{T_E} - \overline{T_C}\right)} \tag{3}$$

$$\dot{q} = \frac{Q}{n\pi d l_{\mathrm{eva}}} \tag{4}$$

The thermal conductivity, λ, for the two vertical orientations PHP is shown in fig. 6. The effective thermal conductivity for both 8-turn and 48-turn PHP is 15652 W/mK and 12328 W/mK, respectively. From the above results 8-turn PHP gave higher thermal conductivity over 48-turn PHP. The difference between the two different PHP with 48-turn were discussed in the upcoming section.

Two PHP configurations

Configurations of parallel and series were two configurations are shown in the figs. 7(a) and 7(b), for a 48-turn PHP.

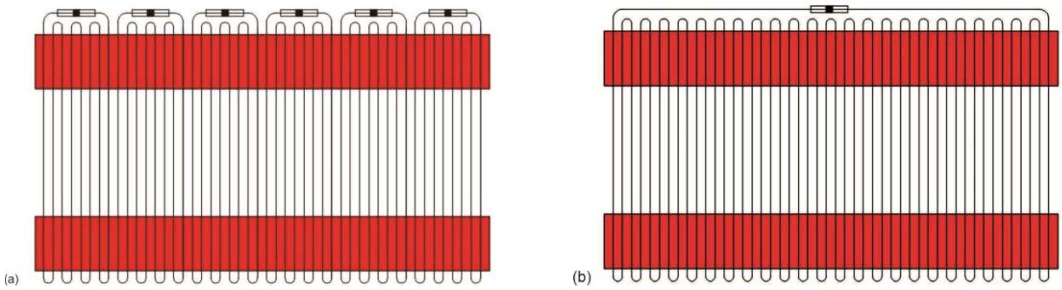

Figure 7. (a) Parallel configuration for PHP and (b) series configuration for PHP

The working fluid will pass in each and every 8-turn as six 8-turn PHP are connected in parallel configuration, was shown in fig. 7(a). In order to progress the heat load between evaporator and condenser, the combined PHP would perform simultaneously. Predicting the effective thermal conductivity at any heat flux is feasible, as the displacement of the working fluid would be autonomous for each distinct 8-turn PHP. When compared with single 8-turn PHP, the parallel PHP configuration does not alter the overall heat flux.

The working fluid would move through the entire 48-turns long channel, as six 8-turns of PHP are in series configuration, a 48-turn PHP experiment remained revealed in fig. 7(b). In present performance, thermal performance has been predicted in serial configurative PHP. Ultimately, the thermal performance of 8-turn PHP is good than in the vertical orientation, series configured a 48-turn PHP. A faceable interpretation for the performance was furnished by the envisage motion of working fluid. The distinct number of turns does not get much impression on the oscillation motion at a low heat load start. The complication to design a unidirectional circulation in entire PHP will be increased by additive turns, followed by two reasons, initially, inorder to overcome flow resistance. The recommended driving force is higher as it has long distance and more turns. Secondly, in advance forming the unidirectional flow the velocity of the fluid run by the variation of pressure is random in every direct method. Even though, the pressure in equity amid channels becomes durable. Unpredictability besides improves in a 48-turn PHP. In adjoining channels it is more likely to have absorber flow. Hence, there is the degradation in the probability of forming unidirectional flow. In the terms of capacity of heat transfer and effective thermal conductivity in a vertical orientation, more effective is the parallel set-up. The parallel configuration enables the favorable use of current experimental results in order to adopt the separate application needs.

Conclusions

According to consequences for the number of turns based on the heat transfer output on helium cryogenic PHP, a 48-turn helium PHP study were used in place. Capillary tube made of stainless steel by an external and internal diameter of 0.8 mm and 0.5 mm. Fixed addicted to 48 parallel channels where constructed by PHP prototype. The evaporator, condenser then adiabatic areas are 50, 50, and 100 mm in length. Among vertical orientation, PHP is operated.

- In addition to the PHP helium of the number of turns, the phenomena of dry-out matters. Temperature of evaporator and condenser sections against graph of heating power, there is a point called *dry out point*. For the 48-turn PHP, that are the *semi dry out* condition through the broad heat inputs. During a *semi dry out* the temperature variance is very high and thus PHP could not serve as an efficient heat transfer system.
- By raising the number of turns up to 48-turns, between evaporator and condenser, the temperature difference will decrease automatically the huge efficient usage of cooling power is contributed by the small temperature difference in condition cooled cryogenics schemes.
- Owing to raise the working fluid, PHP heat transfer efficiency, can upsurge through increasing the number of turns up to 48-turns. Ultimately, there is decrease maximum effective thermal conductivity.

Configurations of parallel and series were definite by taking the example for PHP of 48-turn. The PHP examined for work may be configured among the 8-turn PHP connected in series. Along a whole 48-turn tube, the whole fluid will flow. The usage of six 8-turn PHP to transfer the heat together is called parallel configuration. In each and every, six 8-turn PHP, the working fluid will circulate. Then, with regard to optimum thermal conductivity effectiveness and capacity of heat transfer rate, the parallel formation in the vertical orientation is more efficient compared to the series configuration.

Nomenclature

D_{crit} – critical diameter of the capillary tube [m]
d – inner diameter of PHP [m]
g – gravitational acceleration [ms^{-2}]
LFR – liquid fill ratio [%]
L – length of adiabatic section [m]
l_{eva} – length of evaporator section [m]
n – number of turnes
P_1 – pressure of buffer tank after charge helium gas [Pa]
P_{1*} – pressure of buffer tank before charge helium gas [Pa]
Q – heat load added to evaporator by the heater [W]
$\dot{q}$ – heat flux added to evaporator by the heater [Wm^{-2}]
R – ideal gas constant
T_1 – temperature of the buffer tank [K]
T_{C} – temperature of condenser of PHP [K]
T_{E} – temperature of evaporator of PHP [K]
V_1 – volume of the buffer tank [m^3]
V_{PHP} – volume of the PHP [m^3]

Greek symbols

λ – effective thermal conductivity [Wm^{-1}K^{-1}]
ρ_{v} – vapor density [kgm^{-3}]
ρ_l – liquid density [kgm^{-3}]
σ – surface tension [kgs^{-2}]

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